Results from the *Herschel* DIGIT Open Time Key Program

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ABSTRACT

Results obtained in the framework of the DIGIT (*Dust, Ice and Gas in Time*) *Herschel* open time key program are presented, with a focus on proto-planetary disks. The results summarized here show the richness of the infrared spectral range for the study of proto-planetary disks and the potential of *SPICA* in this area.

1. THE DIGIT OPEN TIME KEY PROGRAM

The DIGIT (*Dust, Ice and Gas in Time*) open time Key program (Principal investigator Neal J. Evans) uses the *Herschel Space Observatory* (Pilbratt et al. 2010) to study the evolution of young stellar objects towards planetary systems. The unprecedented sensitivity of *Herschel* allows for a comprehensive inventory of gas and solids in the environments of young stars, thus probing the changing physical and chemical conditions as star- and planet formation proceed. The DIGIT sample consists of 94 objects including protostars, Herbig Ae/Be stars, T Tauri stars, and weak-lined T Tauri stars. Many of the stars in the DIGIT sample are well characterized at other wavelengths; in particular *Spitzer* data are available. The new *Herschel* data can thus be put into the context of these existing data. Most *Herschel* observations were taken with the PACS instrument (Poglitsch et al. 2010), but also data with HIFI (de Graauw et al. 2010) and SPIRE photometry (Griffin et al. 2010) was obtained. First results of the DIGIT program were published by van Kempen et al. (2010) and Sturm et al. (2010). In several recent papers analyses are presented of the different categories of objects included in the DIGIT sample, e.g. weak-lined T Tauri stars (Cieza et al. 2013), proto-planetary disks (Fedele et al. 2013; Meeus et al. 2013), and embedded protostars (Green et al. 2013). A summary of results of the DIGIT program was presented by Bouwman & Evans (2012). Several other *Herschel* key programs also address the evolution of young stars, in particular the GASPS (Dent et al. 2013) and the *WISH* (van Dishoeck et al. 2011) programs. In this paper, we focus on results obtained for the proto-planetary disks sample. Figure 1 shows the infrared spectrum of one of the best studied objects in the sample, the Herbig Ae/Be star HD 100546.

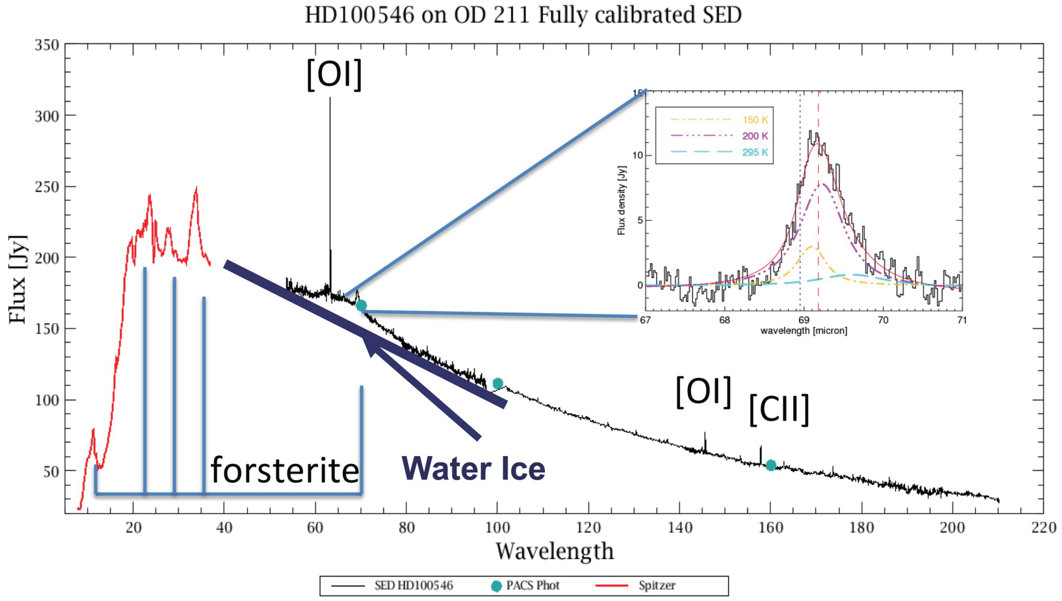

Figure 1. Spectral energy distribution of the Herbig Ae/Be star HD100546, showing the *Spitzer* IRS spectrum, and the full PACS scan (Bouwman et al., in preparation). The inset shows the 69 μm forsterite band (Sturm et al. 2010).

2. EVOLUTION OF PROTO-PLANETARY DISKS

Planet formation has a profound influence on the structure and composition of proto-planetary disks, both of the gas and the solids. Small sub-micron sized grains that enter the disk from the molecular cloud grow by coagulation, and subsequently settle to the disk mid-plane. Radial and vertical mixing cause material to be transported from inner disk to outer disk regions, and from the mid-plane to the disk surface. Grain-grain collisions cause larger grains to be fragmented to smaller particles in a delicate balance between grain growth and destruction. In the inner disk chemical and thermal processing of primordial material takes place, (partially) erasing the memory of its origin. This processed material is mixed to the outer regions and becomes incorporated into planetesimals, that carry the imprint of these local conditions.

As planets form and migrate, they clear parts of the disk, creating gaps and holes. Such disks are often classified as transitional disks, as their spectral energy distribution shows a lack of emission in the near- and mid-infrared compared to continuous disks. Disk gaps complicate the accretion of gas and dust from the outer regions to the central young star, allowing for a widely varying spatial composition of the material in the disk. For instance, small grains can cross gaps more easily than larger grains, and proto-planets can cause azimuthally varying dust density and composition. Some disk gaps are found to be filled with gas (e.g. Casassus et al. 2013), while the signature for solid material is less obvious. The composition and chemistry that takes place in these disk gaps is interesting, since the material is less shielded from stellar photons due to the decrease in the local dust opacity.

The *Herschel* wavelength range is particularly suited to study the gas and dust emission from the warm disk surface layers and cooler material from e.g. the outer regions of proto-planetary disks, and thus complements the diagnostics provided by e.g. *Spitzer*, ALMA, and ground-based near-infrared spectroscopy and imaging. As an example, we show in Figure 1 the infrared spectrum of HD100546 (Bouwman et al., in preparation), showing both dust and gas emission from its proto-planetary disk.

3. GAS IN PROTO-PLANETARY DISKS: A DIGIT VIEW

Table 1 gives an overview of the gas species detected in the DIGIT sample, divided between the more massive Herbig Ae/Be stars and the T Tauri stars. The [C II] fine structure line was not covered in all spectra, and some of the emission may be of a diffuse nature and not associated with the disk.

The relatively low fraction of Herbig Ae/Be stars with H_2O detections (compared to T Tau stars) and the relatively higher detection rate of OH for these stars suggests that water may be dissociated to OH, perhaps as a result of the stronger radiation field of the more luminous Herbig Ae/Be stars. However we note that a substantial fraction of the Herbig Ae/Be stars in the DIGIT sample (previously classified as “flaring” or Meeus group I; Meeus et al. 2001) have recently been recognized to be transitional disks with substantial clearing of the inner disk regions (Honda et al. 2012; Maaskant et al. 2013), which may hamper a direct comparison to the T Tau stars in the sample. Fedele et al. (2012) model the OH and water emission in HD 163296 and find that it is most likely located in the upper layers of the disk atmosphere at distances of 15 to 20 AU from the star.

When applying PDR models to the detected fine structure line emission of [O I] and [C II], constraints on the gas densities and the radiation field can be derived (Fedele et al. 2013). The DIGIT data suggest typical densities of the order of 10^5 cm^{-3} and G_0 between 10^3 and 10^7. Since some of the [C II] emission may be diffuse, these values are in some cases lower limits.

CO is sometimes detected to very high rotational quantum numbers, probing gas at high excitation. In the Herbig Ae/Be stars, modeling of the CO ladder shows that the gas and dust in the upper disk layers must be decoupled, with T_{gas} larger than T_{dust} (e.g. Bruderer et al. 2012). Interestingly, CO is detected only in the “flaring disks” among the Herbig Ae/Be stars (see Meeus et al. 2012). These objects also show strong PAH emission. As mentioned above, these “flaring” disks may in fact be transitional disks. In several of these “flaring” disks a lack of CO ro-vibrational emission from the inner disk regions has been reported, suggesting lower gas surface densities in the inner disk (Brittain et al. 2009; van der Plas et al. 2009). The detected CO emission in these disks is more likely associated with a disk wall at 10 to several tens of AU, and with the outer disk, or possibly CO gas in the disk gap.

Finally, CH^+ is detected in two Herbig Ae/Be stars. The first detection of CH^+ was reported by Thi et al. (2011) in HD100546, using data from the GASPS *Herschel* open time Key Program. They model the CH^+ in HD100546 using a physical/chemical disk model and find that the CH^+ is probably associated with the disk wall at ∼13 AU, extending to ≈ 30 AU. Using a slab model and an update of the flux calibration (resulting in different CH^+ line fluxes for HD 100546 compared to Thi et al. (2011)), Fedele et al. (2013) arrive at a location of the CH^+ emission of several tens of AU. Fedele et al. (2013) add the detection of CH^+ in HD97048 based on DIGIT data.

4. DUST EMISSION FROM PROTO-PLANETARY DISKS

The Spectral Energy Distribution of proto-planetary disks is dominated by thermal infrared emission from the dust in the disk. At mid-infrared wavelengths (typically 10 to ∼100 μm) the warm dust particles in the disk atmosphere dominate. Apart from a strong continuum, dust grains also produce spectral features (dust bands) as a result of the vibrational resonances in the solid. The wavelength and strength of these dust bands depend on the chemical composition, lattice structure, size and shape of the dust particles. Depending on the thermal history of the grains, the lattice structure can either be amorphous (as is the case for e.g. interstellar silicates), or crystalline. The infrared spectral region is very rich in strong resonances of the most abundant dust species, and offers an ideal hunting ground for the mineralogy of disks. Below we focus on crystalline silicates and water ice.

The formation of crystalline silicates requires annealing of amorphous silicates to temperatures above the glass temperature of ~1000 K, or gas-phase condensation (typically at temperatures of ~1500 K). Crystalline silicates were found to be abundant in many proto-planetary disks (e.g. Malfait et al. 1998; van Boekel et al. 2005; Juhász et al. 2010; Sicilia-Aguilar et al. 2011; Furlan et al. 2011), and because they are not found in interstellar space they must have been formed in the disk. Tracing the location and abundance of crystalline silicates may thus probe the thermal and mixing history of proto-planetary disks. In addition to crystalline silicates, previous missions have also suggested the presence of hydrosilicates in one Herbig star, HD142527 (Malfait et al. 1999).

So far studies of dust bands using *Herschel*/PACS have been mostly limited to a narrow band of forsterite (Mg_2SiO_4) near 69 μm (Sturm et al. 2010; Sturm et al. 2013). Weaker and broader bands (detected with *ISO*-LWS in some objects) were more difficult to study in PACS data because their analysis critically depends on a reliable relative spectral response. However recent improvements in the calibration now make it possible to study other bands. We show in Figure 1 the PACS full scan of HD100546 (Bouwman et al., in preparation). Apart from the 69 μm forsterite band previously reported by Sturm et al. (2010), the spectrum also shows a weak broad band near 62 μm which can be attributed to crystalline water ice.

The shape and wavelength of the 69 μm forsterite band is very sensitive to the presence of Fe in the lattice. Forsterite is the Mg-rich end member of the olivine family, which chemical formula $Mg_{2x}Fe_{2-2x}SiO_4$. Even a small addition of Fe of a few per cent moves the band by several microns, and so this is a very sensitive probe of the chemical composition of crystalline olivine in disks. The width of the band is sensitive to the temperature of the grains. The *Herschel* data show that the amount of Fe is less than 2 per cent (with the notable exception of AB Aur), and fairly warm (100–200 K Sturm et al. 2013). In terms of chemistry, Fe has not played a role in the gas-phase condensation of these grains, or it has been removed from the lattice during annealing. The chemical composition of these grains resembles those seen in solar system comets and interplanetary dust grains, and is not consistent with the more Fe-rich olivine found in meteorites that originate from the asteroid belt. Using a detailed radiative transfer model, Mulders et al. (2011) show that the forsterite in HD 100546 is located on the disk surface layers near the inner radius of the outer disk, and probably related to the presence of the disk gap.

Water ice shows strong resonances in the near- and far-infrared. Here we focus on the along wavelength bands near 44 and 60 μm, probing a cold water ice reservoir in disks. The shape and wavelength of the bands is sensitive to the lattice structure and thermal history of the water ice. The detection of crystalline water ice in disks opens the exciting possibility of studying the snow line in proto-planetary disks. In addition, it allows for a more complete census of water in disks than can be obtained from water vapor measurements. Indeed, prominent crystalline water ice bands at 44 and 60 μm were already detected by *ISO* in the Herbig star HD 142527 (Malfait et al. 1999). Since the temperature of the water ice in HD 142527 was found to be below the crystallization temperature, substantial thermal processing must have occurred in its outer disk.

Water ice was detected in the PACS spectrum of the T Tau star GQ Lup (McClure et al. 2012), which when confirmed represents the first detection of the 60 μm water ice band using *Herschel*. The *Herschel*-PACS spectrum of HD 142527 confirms the presence of a large reservoir of water ice in its disk (Min et al., in preparation). However, the broad emission at ~110 μm reported by Malfait et al. (1999), which was attributed to hydrosilicates, is not found in the PACS data. Bouwman et al. (in preparation) report the detection of crystalline water ice in HD 100546. A preliminary analysis of the water ice shows that it is located slightly beyond the disk wall at ~20 AU and with an abundance of ~1 per cent (Mulders, private communication).

5. THE PROSPECT OF *SPICA*

The tremendous gain in sensitivity that *SPICA* (Nakagawa et al. 2011) will provide opens the possibility to study gas and dust in a large range of objects. In particular full spectral scans using *Herschel* could only be obtained for the brightest,

Table 1. Gas species detected in the DIGIT disk sample. Numbers given indicate the number of detections/number of stars observed. See Fedele et al. (2013) and Meeus et al. (2013).

species	Herbig Ae/Be	T Tauri
[O I]	20/22	7/8
[C II]	7/20	2/4
OH	7/22	5/8
CO	5/22	4/8
H_2O	3/22	4/8
CH^+	2/22	0/8

most massive disks, with already very rewarding results. Extending the studies of disks to lower mass stars and even brown dwarfs is an important step in quantifying the connection between planet formation and the architecture of mature planetary systems. The wide wavelength range that *SPICA* will offer allows for a comprehensive inventory of gas and dust from the warm inner disk regions (the region of terrestrial planet formation, tracing e.g. organic chemistry), to the colder outer regions where gas giants and icy planets form. Lastly, *SPICA* will be the first space observatory since *ISO* to provide access to the important ~35 to ~55 μm wavelength region, which contains a wealth of diagnostic tools.

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